The Strait of Juan de Fuca as Seen from Satellite

Kathleen A. Edwards and Parker MacCready
Department of Oceanography, University of Washington

Abstract
Coastal mixing is of practical interest in the Strait of Juan de Fuca due to the industrial sites on its shores and its heavy shipping traffic. One source of mixing in the Strait is coastal topography. As water is driven through the Strait by the tides, it is stirred by irregularities on the coastal wall, such as 1-km wide underwater bumps. We present observations of this mixing process which were collected on a June 2000 research cruise. During surveys along the Strait's northern slope, the ship's ADCP recorded velocity profiles throughout the tidal cycle. Supplementing these data were CTD casts, moored ADCP measurements, and thermistor chains at the eastern mouth of the Strait. This paper presents the picture of coastal mixing which is captured by these data. The goals of the study are 1) to supplement limited observations within the Strait and 2) to understand the effect of wall roughness on tidal flows.

Introduction
The Strait of Juan de Fuca connects the Puget Sound to the Pacific Ocean (Figure 1). A deep channel off its western mouth marks it. The Strait becomes more shallow to the east. South of the San Juan Islands, it is interrupted by shallow shoals, and sills limit water passage to and from the Puget Sound. In order to study mixing and transport in this important waterway, fieldwork has been conducted in the Strait from 1996 to present. Led by Drs. Richard Dewey and Chris Garrett at the University of Victoria and Dr. Rich Pawlowicz at the University of British Columbia, summertime oceanographic cruises have observed the physical oceanography and chemistry of the Strait. As well, instrumented moorings have collected velocity time series at locations within the Strait. The current work focuses on the June 2000 time period when a cruise collected observations at the locations plotted in Figure 1.

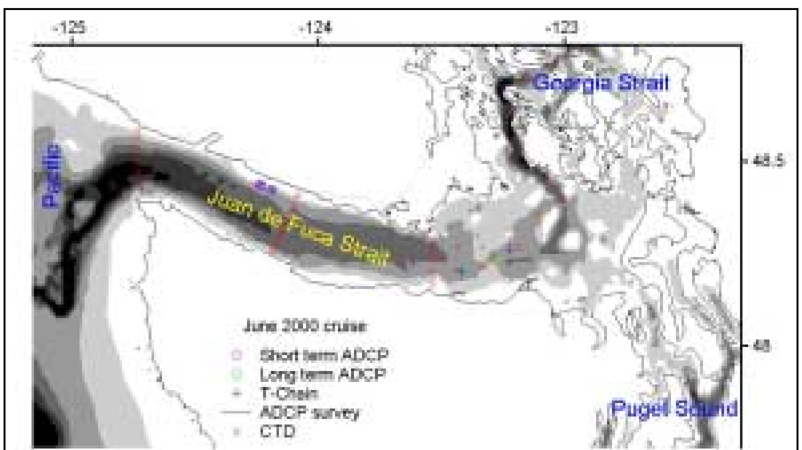

Figure 1. The Strait of Juan de Fuca. Shading indicates water depth. Locations of observations taking during the June 2000 cruise are labeled: acoustic Doppler current profiler (ADCP) moorings and survey, moorings which recorded temperature at different water depths (T-Chain), and current/temperature/density profiles (CTD).

Because a ship or a mooring records data at a single point, a useful supplement to these data is maps of properties that are recorded instantaneously by satellite. The goal of this paper is to present the satellite datasets that are most useful to studying the physical oceanography of the region. As well, the oceanographic features that can be identified in the satellite maps are listed. Information on obtaining the data, most of which is freely available, is given.

Methods

Of the three satellite datasets that are most useful to study the Strait (ocean temperature, roughness, and color), we will show examples of the first two only.

Sea Surface Temperature

The Advanced Very High Resolution Radiometer (AVHRR) has been carried aboard a series of NOAA satellites. The sensor measures upwelling radiation at different spectral bands, known as channels. Channels 1 and 2 record visible and near-infrared radiation, while channels 3, 4 and 5 record thermal radiation. The data are available at 1.1-km resolution, approximately daily. Sea surface temperature (SST) is derived from the thermal-channel data based on the fit of these to SST observed by oceanographic buoys. From the many algorithms, the NOAA non-linear algorithm (NLSST) was chosen for the current study (Li et al, 2001; Walton et al, 1998). The sensor's view of the ocean surface is blocked by cloud. There are established tests to identify cloudy pixels. Some identify clouds by their sharp spatial gradients, but will also mistakenly eliminate SST fronts, which are common in the Strait. For this reason, pre-derived SST fields, such as are available through NOAA's CoastWatch program (http://sgiot2.wwb.noaa.gov/COASTWATCH), must be used with caution. We have chosen to derive SST from the raw data.

Ocean Roughness

Images of are ocean roughness are obtained by the synthetic aperture radar (SAR) which is carried aboard satellites. SAR emits radar pulses, which are scattered off of gravity-capillary waves. The images display this backscatter. Processes in the ocean and atmosphere which affect the gravity-capillary wave field can be identified in SAR images (Beal and others 1981; Johannessen and others 1996). These include variations in the wind stress, surfactants floating on the ocean surface, longer waves such as internal gravity waves or swell, current shear, and atmospheric stability variations. When winds are light (less than 2m/s), the backscatter is too low to be imaged by SAR, while very strong winds saturate the wave field. Lines of surface film are useful as a tracer for water currents' structure, but are torn apart in high winds.

The SAR images have high spatial resolution (30-100 m) but low temporal resolution (approximately weekly). Interpreting the images is complicated because both atmospheric and oceanic processes have SAR signatures. The sensor can view the ocean surface through cloud. Users can apply for an account to obtain the images from the Alaskan SAR Facility (http://www.asf.alaska.edu/).

Ocean Color

Ocean color is recorded by the SeaWiFS (Sea viewing Wide Field-of-view Sensor) at 1.1-km resolution. The data, which will not be presented here, are freely available from the Goddard Distributed Active Archive Center (DAAC) at http://xtreme.gsfc.nasa.gov/data/dataset/SEAWIFS/index.html. The sensor's view of the ocean surface is blocked by cloud. Images are available every few days. Processed images of the Washington coast and the Strait can be obtained from http://boto.ocean.washington.edu. These data will not be presented in this paper.

Results

Sea Surface Temperature

To demonstrate the features that AVHRR makes visible, we present two images close in time to the June 2000 cruise. The image in Figure 2a was taken at 9:33 am PDT on 26 June 2000 during a predicted ebb tide in the eastern Strait (-0.59 m/s). To the west, a cold upwelling filament off Cape Flattery follows a deep trench and is likely due to topographic upwelling. Within the Strait, sea surface temperature is spatially variable, consisting of 10-km diameter warm. In the eastern Strait, SST is several degrees warmer. The warm patches are approximately 5 km in diameter, which is the size of the underwater shoals. Locally cold water at Victoria and Race Rocks is due to strong vertical mixing. Dungeness Spit shelters markedly warmer water.

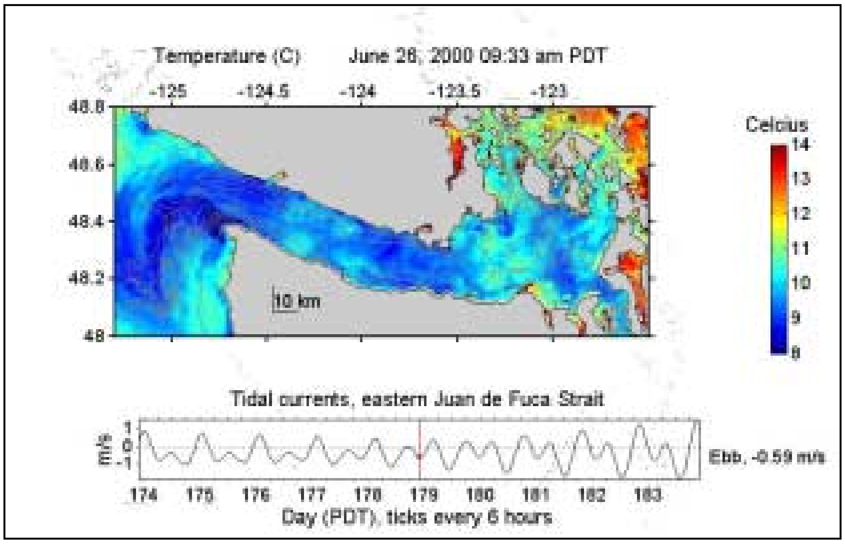

Figure 2a. Top: sea surface temperature from AVHRR. Water depth contours are overlaid. Bottom: predicted tide (positive = flood). Vertical line marks 9:33 am PDT on 26 June, 2000, when image was taken.

Figure 2b presents the SST 9 hours later, again for an ebb tide (-0.51 m/s). The cold water off of Cape Flattery is still apparent. The warm patches in the eastern Strait are still present, with locally cold water at Admiralty Inlet and to the south of the San Juan Islands is attributed to vertical mixing. The fact that the image appears approximately 1 degree C warmer than Figure 2a may be a bias and is being investigated.

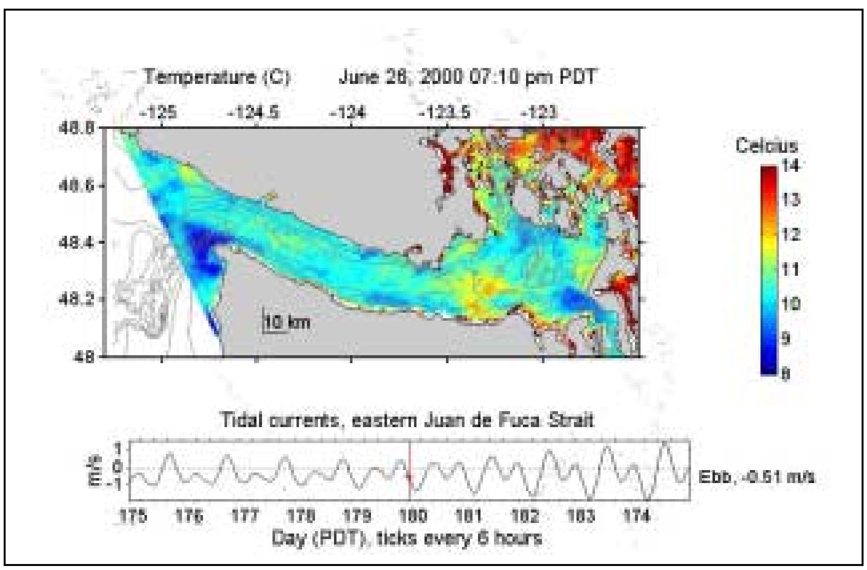

Figure 2b As in 2a, but for an image taken at 7:10 p.m. PDT.

Ocean Roughness

To demonstrate the ocean features which SAR imagery makes visible, several examples are presented and interpreted. In Figure 3, internal waves are made visible by alternating light/dark bands associated with their crests and troughs. The waves, which have a wavelength of approximately 1.5 km, are entering the Strait from the both mouths. They are propagating across the isobaths (Figure 1).

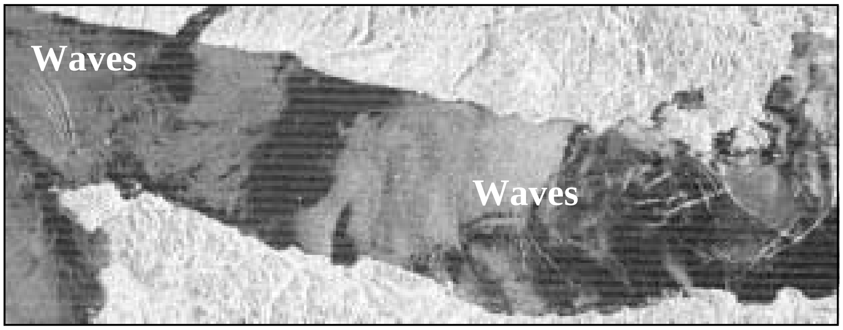

Figure 3 SAR image of ocean roughness (light=rough, dark=smooth) from 26 July 2000.

Figure 4 shows the eastern Strait near Victoria. Fronts are visible as bright, irregular lines south of Race Rocks and off Victoria.

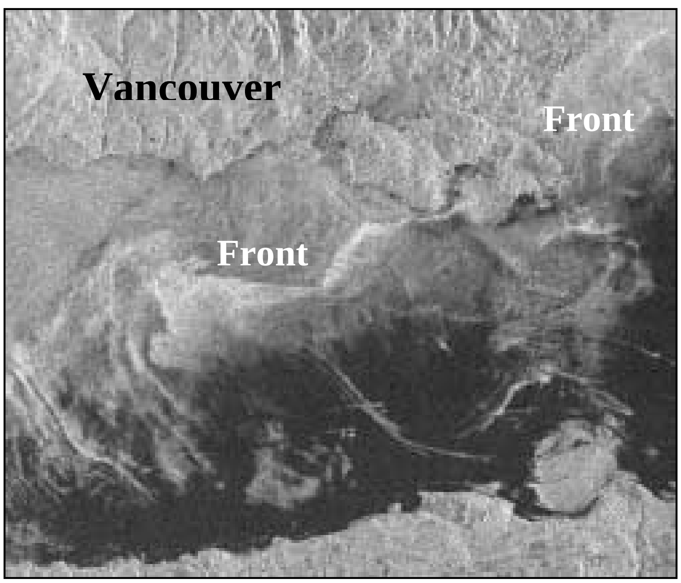

Figure 4 A SAR image showing fronts in the eastern Strait on 31 July, 1999.

Slicks containing natural surfactants are visible in SAR imagery as dark lines. Figure 5 shows slicks off Cape Flattery as well as internal waves entering the western mouth of the Strait.

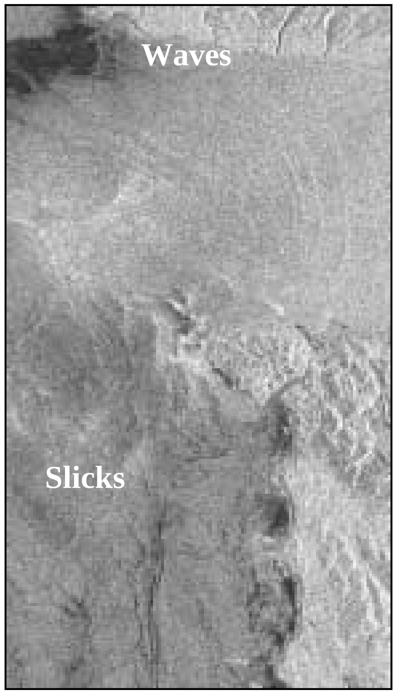

Figure 5 A SAR image of the western mouth of the Strait on 29 June 2000.

Conclusions

Satellite imagery complements *in situ* data such as ship and mooring data from the Juan de Fuca Strait. Due to the Strait's relatively narrow width, the satellite datasets must have high spatial resolution: 1.1 km for AVHRR, 30-100 m for SAR, and 1.1 km for SeaWiFS. The usefulness of these datasets is limited by sparse time sampling or by the inability of a sensor to view through cloud. The raw data are free, in the case of SAR to users with an account at ASF. Providers of the data were listed.

Several images demonstrate which oceanic features can be seen. Despite the 9-hour separation of two AVHRR images, features persisted through the tidal cycle. SST was patchy on the 5 and 10-km spatial scale. The SST patches appear to be associated with topography, especially that of underwater shoals. A cold filament off Cape Flattery followed a deep trench offshore and is attributed to topographical upwelling. Both SST and roughness, the latter imaged by SAR, were more variable at either mouth of the Strait than in the middle. Two sources of variability in roughness were fronts and internal waves, which appeared to propagate across bathymetry.

Acknowledgements

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